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04 ION COMPOSITION FROM VLF PHENOMENA OBSERVED BY ALOUETTE I AND II

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Abstract. The Alouette I and II satellites have receivers capable of observing electromagnetic emissions of very low frequencies. These receivers have observed proton and helium whistlers as well as noise bands that determine the lower hybrid resonance of the ionospheric plasma. The simultaneous observation of two or more of these phenomena can provide sufficient information to determine the electron density and the relative abundance of the major ion constituents at the height of the spacecraft.

Considerable information on the variation with latitude of the ion composition at 1000 km has been obtained from Alouette I observations. The elliptic orbit of Alouette II permits the study of the variation of ion composition as a function of height. In particular the relative abundance of not only protons but also of oxygen and helium ions have been obtained from Alouette II observations. An interesting feature of the results is the measured ratio of helium ion abundance to that of oxygen ions which was found to be about unity at 1000 km in middle latitudes and decreased at greater heights.

Russian abstract see page 632

1. INTRODUCTION

Satellites equipped with receivers capable of observing electromagnetic emissions of very low frequency have provided a valuable new source of information on the composition of the ionosphere. Similar ground-based receivers have been operated for several decades and have provided considerable information on the electron number densities in the magnetosphere. Ground based VLF observations are, however, not particularly sensitive to the effects of positive ions. These effects are most pronounced for VLF waves propagating transversely or in the ion cyclotron mode, but neither of these modes can normally penetrate the lower ionosphere. A receiver within or above the ionospheric F region can observe such waves.

The VLF observations presented in this paper were all obtained from the satellites Alouette I and II. Alouette I was launched into an almost circular 80° inclination orbit at a height of 1000 km. It contains a VLF receiver covering the band from 400 Hz to 10 kHz. This satellite has been in orbit for $3\frac{1}{2}$ years and is still recording VLF signals. The Alouette II satellite was launched on 29 November 1965 into an 80° inclination elliptic orbit with a perigee of 500 km and an apogee of 3000 km. It carries a VLF receiver covering the band from 50 Hz to 30 kHz. As yet only a limited amount of data is available from this spacecraft, but it has already provided significant information on ion composition.

Positive ion composition measurements using VLF have two features of particular significance. The wavelengths of VLF waves within the terrestrial ionosphere are large, thus any perturbation of the medium by the satellite is not likely to introduce appreciable errors into the composition determined from the propagation of such waves. Several of the VLF phenomena to be described are dependant only on the relative abundance of the ion species of the medium rather than on the numerical abundances, as in most other techniques. The greatest drawback to measurements using VLF waves lies in the fact that they are at present dependant on the sporadic occurrence of natural emissions.

2. THE LOWER HYBRID RESONANCE

Early in the lifetime of Alouette I it was found that the VLF receiver frequently observed noise bands that varied systematically with the position of the spacecraft in the geomagnetic field [1]. Usually these noise bands had a sharp lower frequency cut-off that decreased as the satellite moved towards higher geomagnetic latitudes. Comparisons of satellite and ground observations indicated that while noise bands with these characteristics were frequently observed by the satellite receiver they were never observed on the ground. As yet it is not clear how these noise bands are produced although they are frequently triggered or enhanced by whistler mode signals propagating up or down magnetic field lines. Consideration of the characteristics of this noise led Brice and Smith [2] to the conclusion that the lower cut-off frequency of the noise bands is the lower hybrid resonance for the plasma at the height of the spacecraft. This plasma resonance defines a cut-off frequency for propagation transverse to the earth's magnetic field.

The frequency of the lower hybrid resonance (LHR) depends on the electron plasma and gyrofrequency and the harmonic mean mass of the positive ions constituting the plasma in the following way:

$$\frac{1}{f_{\text{hyb}}^2} = \left(\frac{1}{f_{\text{H}}^2} + \frac{1}{f_{\text{N}}^2}\right)\frac{m_{\text{p}}}{m_{\text{e}}}\,\overline{m}_i(\text{eff}) \ , \qquad (1)$$

where $m_{\text{p}}/m_{\text{e}}$ is the ratio of the proton and electron masses and

$$m_i(\text{eff}) = 1 \Big/ \sum_i \frac{A_i}{m_i}\, m_{\text{p}} \ . \qquad (2)$$

A_i is the fractional abundance of the ith ion constituent and m_i is its mass.

Average values of $m_i(\text{eff})$ were obtained from observations made by the Alouette I satellite in the following manner. The cut-off frequency of all LHR noise bands observed in the northern hemisphere by the VLF experiment were scaled and averaged to determine the mean value of the lower hybrid resonance frequency as a function of invariant latitude. Corresponding mean values of f_{N}^2 were obtained from top-side soundings [3] made in the same geographic region and during the same period as the VLF observations. Average values of f_{H}^2 were derived from present knowledge of the geomagnetic field in the geographic region of interest. From these average values of f_{hybrid}, f_{N}^2 and f_{H}^2, the values of $\overline{m}_i(\text{eff})$ shown in fig. 1 were derived using eq. (1). It is seen from eq. (2), and the fact that ΣA_i must equal one, that the ion composition for a two ion plasma can be determined uniquely from knowledge of $\overline{m}_i(\text{eff})$. Since the ionosphere in the region under

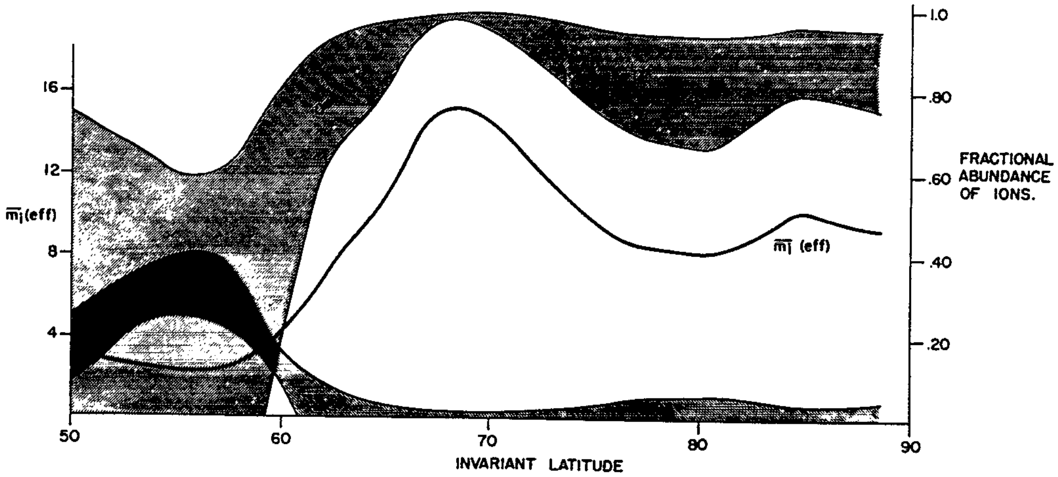

Fig. 1. The variation of $\overline{m}_i(\text{eff})$ with invariant latitude. The shaded areas indicate the regions in which the fractional abundances of O^+ and H^+ must lie to be consistent with the indicated $\overline{m}_i(\text{eff})$.

consideration is believed to be composed primarily of O^+, He^+ and H^+ ions these equations only place limits on the relative abundances of O^+ and H^+. These limits are indicated by the boundaries of the shaded areas in fig. 1.

It must be recognized that the plasma frequency, especially at latitudes above 65°, exhibits marked spatial and day to day variations, hence there is some uncertainty in $\overline{m}_i$(eff) due to its dependance on the plasma frequency. Nevertheless, fig. 1 gives at least a general indication of the relative abundances of O^+ and H^+ at 1000 km over the invariant latitude range from 50° to 90°. From 50° to 60° H^+ is present in appreciable amounts while above 65° the major ion present is O^+.

3. PROTON WHISTLER

Another important discovery made by the Alouette I satellite was the proton whistler [4]. This new type of signal is due to electromagnetic energy that has originated in a lightning discharge and propagated through the lower ionosphere in the right handed whistler mode. In the upper F region this energy is coupled into the left handed ion cyclotron mode. The height at which a given frequency component couples from one mode to the other is determined solely by the positive ion composition of the ionosphere.

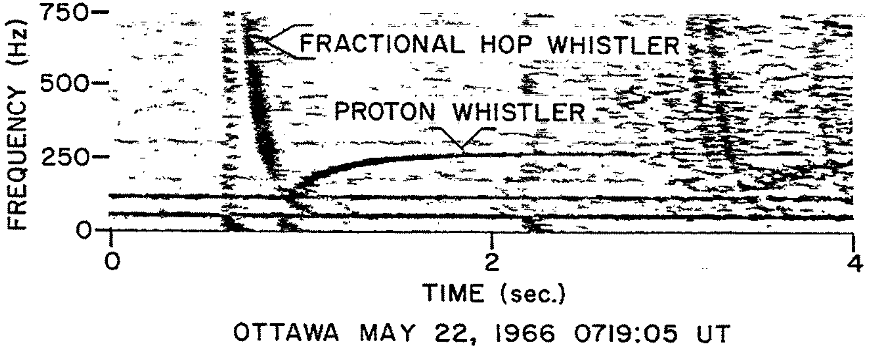

Fig. 2. A proton whistler observed in the Alouette II satellite.

In fig. 2 an example of a proton whistler is shown. The signal labelled fractional hop whistler is due to energy propagating directly from the lightning discharge to the satellite in the right handed whistler mode, and shows the normal whistler dispersion. The signal labelled proton whistler is due to propagation in the ion cyclotron mode and has a dispersion that is just the opposite to that of the right handed whistler mode (i.e. high frequencies are retarded more than lower frequencies). This signal does not extend above the proton gyrofrequency at the height of the satellite since propagation in the ion cyclotron mode is not possible at such frequencies. The group velocity of waves propagating in the ion cyclotron mode is considerably less than that of waves of the same frequency propagating in the right handed whistler mode. Thus the frequency at which the fractional hop signal and the proton whistler signal show no separation in time is the frequency that is coupling from one mode to the other at the satellite height. This frequency (which is termed the cross-over frequency) has been shown by Gurnett et al. [5] to depend only on the positive ion composition of the plasma, and not on the ion density. To a good approximation the cross-over frequency of a proton whistler is dependent only on the relative abundance of protons at the height of the satellite. In passing it should be remarked that the numerical abundance or density of protons can be determined from the dispersion in the tail of a proton whistler [6], but such measurements will not be considered further in this paper.

4. HELIUM WHISTLER

The Alouette II VLF receiver is sensitive to much lower frequencies than the Alouette I receiver. As a result it was able to detect signals of a similar nature to proton whistlers but occurring at frequencies below the helium gyrofrequency at the height of the satellite. These signals have been termed helium whistlers and promise to be a valuable new source of information on ionospheric composition. An example of a helium whistler that has originated from the same lightning discharge as a proton whistler is indicated in fig. 3. Although the spectrogram of the helium whistler is not particularly clear, it is possible from the waveform of this event to determine fairly accurately the frequency at which the helium whistler separates from the fractional hop whistler. This cross-over frequency can be used in conjunction with the proton cross-over frequency to determine the relative abundances of O^+, He^+ and H^+ ions at the height of the satellite. It should be emphasized that the very existence of a helium whistler indicates an appreciable abundance of O^+ or similar heavy ions at this height while an appreciable helium ion abundance is necessary to explain the helium gyro resonance exhibited by this signal.

5. MEASUREMENTS OF ION COMPOSITION

A number of proton and helium whistlers have been observed at middle latitudes (30° - 40°) in the northern hemisphere. So far observations in this region are limited to the early morning and evening hours and were made in the height range from 1000 to 2000 km. In fig. 4 are shown some examples of proton and helium whistlers observed under these conditions. It can be clearly seen from these records that the ratio of the proton cross-over frequency to proton gyrofrequency decreases with increasing height, indicating an increasing proton relative abundance with height. Also indicated on this figure are the fractional abundances of H^+, He^+ and O^+ ions as deduced from the cross-over frequencies of the proton and helium whistlers.

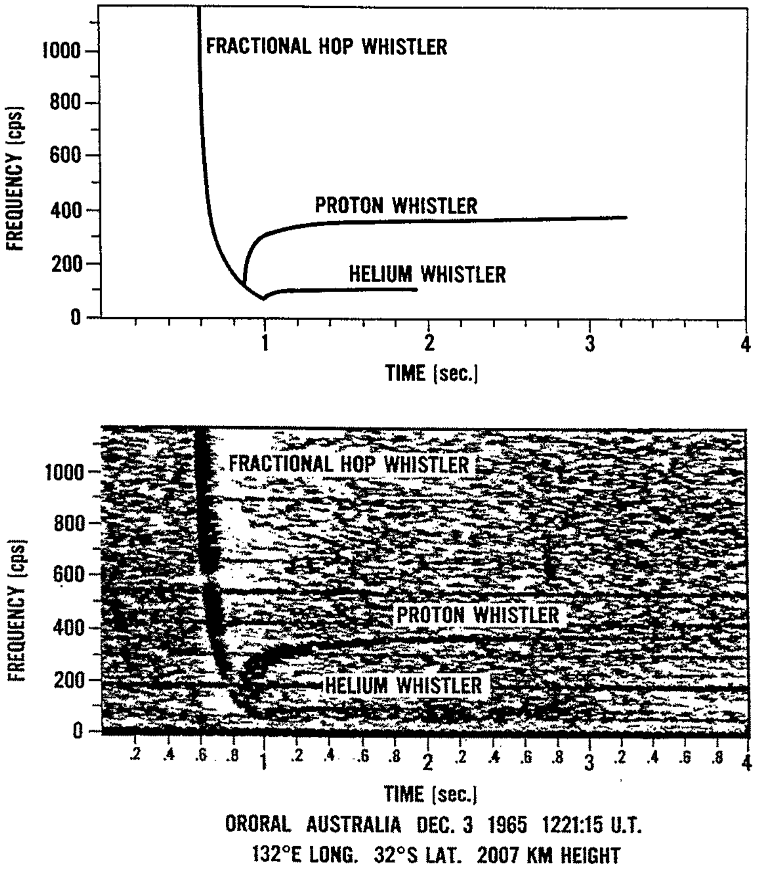

Fig. 3. A helium and proton whistler observed in the Alouette II satellite. The lower part of the figure shows the spectrogram made from the satellite signal. The upper part of the figure depicts an idealization of the different whistler signals.

The absolute errors in these fractional abundances are considered to be not more than ±0.01.

Once the composition of the medium is determined the mean mass of the ionosphere in atomic mass units (amu) can be derived. The variation of the mean mass is shown as a function of height in fig. 5. All of the points below 1250 km on this figure were obtained in the early morning hours whereas the observations at greater heights were made during the evening hours.

In fig. 6 the fractional abundance of protons as a function of height is shown along with the height variation of the ratio of the number of He^+ ions to the number of O^+ ions. Again in considering these data it should be pointed out that the points were not all obtained near the same local time. Even when this limitation is considered this figure seems to indicate that the

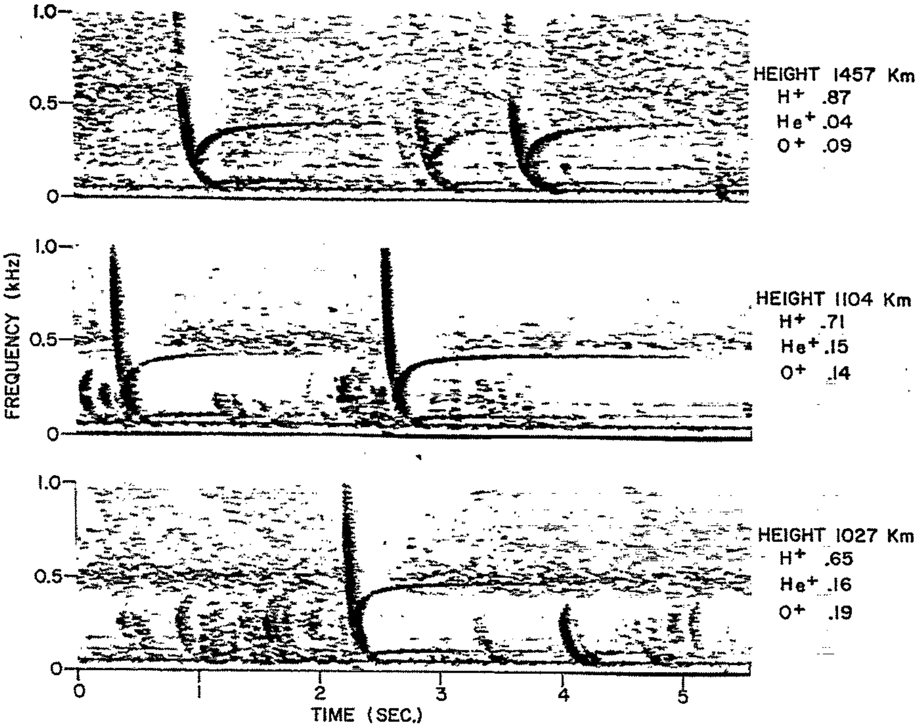

Fig. 4. Some helium and proton whistlers observed at different heights at mid-latitudes. The ion composition derived from each of these whistlers is also indicated.

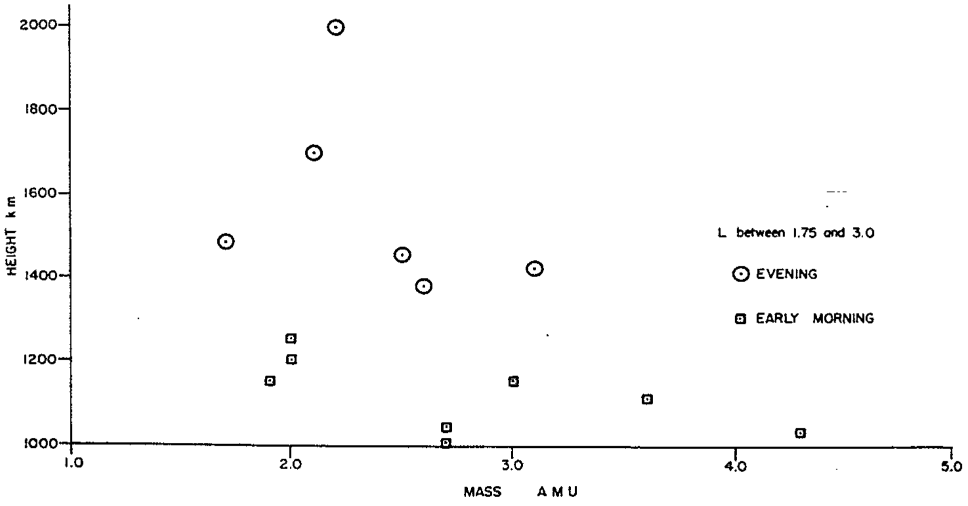

Fig. 5. The variation of mean ion mass with height at middle latitudes.

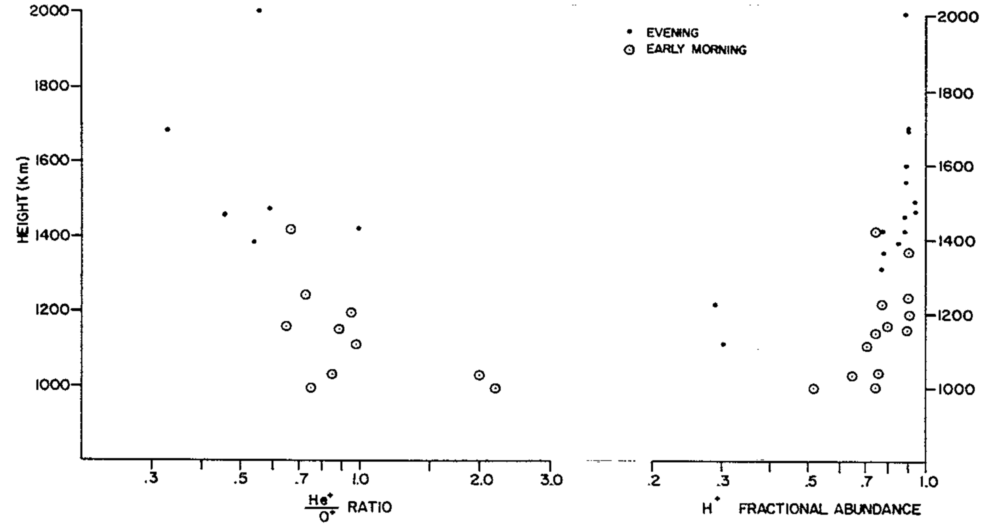

Fig. 6. The variation with height of the fractional abundance of protons and the ratio of He^+ to O^+ concentrations.

ratio of He^+ ions to O^+ ions tends to decrease with height in the range from 1000 to 2000 km. This result is in sharp contrast to what one would expect if the ion species were in diffusive equilibrium throughout this region. Moreover, since these results are for middle latitudes and a limited height range, it makes little difference whether diffusion along field lines or in the vertical direction is considered. It should also be noted that for the region considered here, while the protons are numerically considerably in the majority, the heavier ions O^+ and He^+ still contribute 50% or more to the mass of the medium. Thus in considering parameters such as scale height that depend on the mean mass of the ions a proper understanding of the distribution of these heavier ions that numerically constitute only a small fraction of the medium is essential.

Although much of the information on ion composition that has been presented must be considered as rather preliminary, it does indicate the value and potential of VLF observations in this field. In conclusion it is worth indicating the regions in which these different VLF phenomena tend to be found. This can be seen from fig. 7 which indicates the places where ion whistlers and LHR noise bands have been seen to date by the Alouette satellites. Generally ion whistlers are observed throughout the entire height range covered by the satellites but are concentrated at low and middle latitudes. They have not been observed beyond 60°. The LHR noise tends to occur primarily at high latitudes, but there is a sizeable latitude region in which both phenomena may be observed. This figure also indicates that LHR noise bands are found over a considerable height range. Thus there is a good opportunity for intercomparison of the data obtained from these two types of observations.

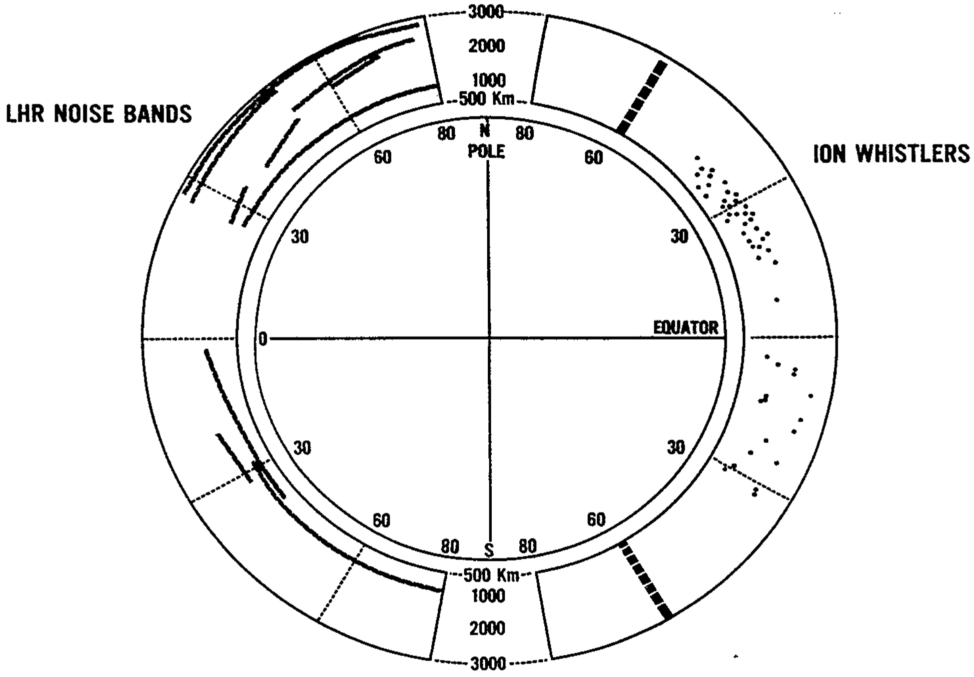

Fig. 7. The latitude and height regions in which LHR noise bands and ion whistlers have been observed by the satellites Alouette I and II.

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Резюме: Алуэтт I и Алуэтт II имеют радиоприемники, приспособленные для наблюдений электромагнитного излучения очень низких частот. Эти приемники регистрировали протонные и гелиевые свистящие атмосферики, так же как и полосы радиошумов, которые характеризуют более низкочастотный смешанный резонанс ионосферной плазмы. Одновременное наблюдение двух или более из этих явлений может дать достаточную инфор-

мацию для определения концентрации электронов и относительного содержания главных ионных компонентов на уровне орбиты космического аппарата.

По наблюдениям Алуэтта I получена существенная информация о широтных вариациях ионного состава на высоте 1000 км. Эллиптическая орбита Алуэтта П дает возможность исследовать ионный состав в зависимости от высоты. Из наблюдений Алуэтта П в частности получено относительное содержание не только протонов, но также ионов кислорода и гелия. Интересной особенностью результатов является измеренное отношение содержания ионов гелия к содержанию ионов кислорода, которое на высоте 1000 км в средних широтах оказалось около единицы и уменьшается на больших высотах.

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